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Infrared Photometry and Dust Absorption in Highly Inclined Spiral Galaxies

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ABSTRACT

We present JHK surface photometry of 15 highly inclined, late-type (Sab-Sc) spirals and investigate the quantitative effects of dust extinction. Using the $J-H$, $H-K$ two-color diagram, we compare the color changes along the minor axis of each galaxy to the predictions from different models of radiative transfer. Models in which scattering effects are significant and those with more than a small fraction of the light sources located near the edge of the dust distribution do not produce enough extinction to explain the observed color gradients across disk absorption features. The optical depth in dust near the plane as deduced from the color excess depends sensitively on the adopted dust geometry, ranging from $\tau = 4$ to 15 in the visual band. This suggests that a realistic model of the dust distribution is required, even for infrared photometry, to correct for dust extinction in the bulges of nearly edge-on systems.

1. Introduction

Observational studies of the bulges and inner disks of spiral galaxies are severely hampered by extinction due to dust in the disk. Several recent works have demonstrated the importance of correctly treating extinction effects. For example, while surface brightness profiles can be fit to obtain morphological parameters, the presence of dust can make

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the measurement of these parameters sensitive to wavelength (Byun *et al.* 1994; Evans 1994). Surface photometry can also be used to estimate the mass distribution of the inner galaxy in order to understand dynamical influences on the bulge. However, light blocked by dust can exacerbate disagreements with kinematical mass estimates and thus suggest the presence of more dark matter than is actually required to explain the rotation curve (Barnaby & Thronson 1994). The effects of dust on broad-band colors are similar to those arising from changes in metallicity and/or age, so the colors and color gradients provided by multiwavelength images may contain little or no conclusive information about stellar populations. Clearly, an understanding of extinction effects is a necessary prerequisite to using the basic properties of bulges as indicators of their structure, stellar content, and history.

In late-type spirals, neither the quantity of dust nor its distribution with respect to the stellar component is precisely determined. Radiative transfer models for plane-parallel and spherically symmetric geometries predict that the amount of dust needed to produce a given reddening depends sensitively on whether the dust lies in front of the luminosity sources or is mixed with them in various ways (Jansen *et al.* 1994; Witt *et al.* 1992, hereafter WTC92). Similar calculations for spiral galaxies consisting of a bulge, a disk, and a disk absorbing layer show that the observed extinction depends on both the optical depth in dust and the structural parameters of the absorption layer (Kodaira & Ohta 1994; Ohta & Kodaira 1995). These calculations and a recent model of the dust in NGC 4594 suggest that it may be necessary to represent the absorbing material with a ring structure (Ohta & Kodaira 1995; Emsellem 1995). Scattering can also have a significant effect on the observed surface photometry and colors, especially at wavelengths where the albedo of dust grains is large (WTC92, Byun *et al.* 1994, Emsellem 1995). Extinction effects in models that include scattering tend to be less severe than in models with no scattering because light scattered into the line of sight partially compensates for absorption and reddening. A suitable representation of the dust component should be able to explain observed reddening effects over a long spectral baseline.

We have begun an extensive study of the structure and kinematics, and evolutionary history of bulges in highly inclined galaxies, some of which show boxy or peanut-shaped morphology. Bulges in late-type spirals, which suffer from the most significant extinction effects, are of particular interest because the disk component dominates the gravitational potential and therefore the history of the bulge and disk may be coupled. In this first paper, we present infrared surface photometry and explore the characteristics of the dust absorption features. Our goal here is to provide quantitative estimates of the observed extinction and reddening in these systems. Once we have determined how to correct for the effects of dust, we will investigate several proposed bulge formation mechanisms,

including disk instabilities, dissipational collapse from the protogalactic gas cloud, or the accretion of small satellites (e.g., Jones & Wyse 1983; Quinn & Goodman 1986; Combes *et al.* 1990; Merritt & Sellwood 1994). These processes would produce distinct signatures in bulge morphology and stellar populations, such as boxy shapes or the presence or absence of metallicity gradients. There are also several clues which suggest that some bulges, especially boxy ones, are related to bars in the inner disks of the galaxies that harbor them. Theoretical studies of resonant heating by bar instabilities have concluded that one may see round, boxy, or peanut-shaped bulges depending on the angle between the bar and the observer (Combes *et al.* 1990). Observational evidence for the link between boxy-peanut bulges and bars has been found in the line-of-sight velocity distributions for a few peanut-shaped bulges, which show the expected kinematical signatures of a bar (Kuijken & Merrifield 1995). Additionally, our own Galaxy has a boxy bulge (e.g., Dwek *et al.* 1995) and shows a great deal of evidence for a bar in the inner disk, including studies of the spatial distribution of tracer objects such as Miras (Nakuda *et al.* 1991; Weinberg 1992; Whitelock *et al.* 1991; Whitelock & Catchpole 1992; Stanek *et al.* 1994), models of the asymmetric distribution of gas velocities in the (ℓ, v) plane (Binney *et al.* 1991), the asymmetry in the infrared surface brightness of the bulge (Blitz & Spergel 1991; Weiland *et al.* 1994; Dwek *et al.* 1995) and an excess of microlensing events towards the galactic center compared to models based on an axisymmetric bulge (Paczyński *et al.* 1994). We intend to use our galaxy surface photometry, corrected for extinction, to model the stellar mass distribution in the inner regions of highly inclined spirals in hopes of illuminating the connection between bars and bulges.

This paper is organized as follows. Sec. 2 describes the JHK surface photometry observations, data reduction techniques, and the determination of color profiles across the galaxy bulges. In Sec. 3 we provide details of the radiative transfer models with which our data are compared. Sec. 4 contains the quantitative results from a comparison of color changes along the minor axes of the bulges to model predictions. In Sec. 5, we compare the color changes produced by dust to those implied by a change in stellar populations. A discussion of the results and some implications for the study of galaxian mass distributions are given in Sec. 6.

2. Observations and Data Reduction

2.1. Sample Selection and Observing Procedures

Our sample of 15 galaxies was selected specifically to study the boxy bulge phenomenon in late-type spirals. We restricted the sample to Hubble Types from Sab through Sc

and considered inclinations $i > 65^\circ$ (the range in which the boxy bulge morphology is identifiable). Eight galaxies in the sample have been identified in the literature as having boxy or peanut-shaped bulges (Jarvis 1986; de Souza & dos Anjos 1987; Shaw *et al.* 1990). The remainder were selected from the *Third Reference Catalogue of Bright Galaxies*, hereafter the RC3 (de Vaucouleurs *et al.* 1991), to span a similar range of absolute magnitudes, major-axis dimensions, and inclination angles as the galaxies with boxy-peanut bulges. Table 1 lists some basic properties of galaxies in our sample.

Near-infrared (JHK) images of the bulge and inner disk regions of sample galaxies were obtained from 20–21 and 27–31 December 1993 with the Ohio State Infrared Imager and Spectrograph (OSIRIS) on the 1.5 m telescope at CTIO. The details of the instrument are described by DePoy *et al.* (1993). OSIRIS has a 256×256 NICMOS 3 array detector and was employed in its wide-field mode, which yielded a field of view of $4.5'$ at a scale of ≈ 1.1 arcsec pixel^{-1}. All observations were obtained under photometric conditions.

We observed each galaxy using an alternating sequence of sky and on-source positions. The sky and galaxy frames were taken with positional dithering so that bad pixels in the array could be filtered out when the frames were combined. Exposure times were set to ≈ 4.9 sec in each filter, so that the count level of the sky plus galaxy nucleus was always less than half the saturation level of 32,000 counts. For these exposure times, the typical sky levels in the J, H, and K filters were 1000, 1500, and 5000 counts respectively. The total on-source integration times for each galaxy in each filter are given in Table 1. The total integration time on the sky was approximately 2/3 of the total time on the source; sky observations were made at intervals of 90 s during the galaxy observations.

2.2. Data Reduction

We performed all steps in the data reduction using the VISTA package (Stover 1988). The first step was to apply a linearity correction to each raw data frame, which was a quadratic polynomial in pixel intensity amounting to less than 2% at the brightest typical exposure levels. All frames were then scaled to a common exposure time using the true integration time[3] for each exposure.

We obtained multiple exposures of the nightly twilight sky in each filter to serve as

[3]The length of sequential exposures in OSIRIS varies by ≈ 0.1 s. OSIRIS records the exact exposure time for each image, storing it as the value of a designated pixel. The extraction of the exposure time was performed before the linearity correction.

flatfield corrections. A zero-exposure bias frame was subtracted from each twilight sky frame, then they were multiplicatively scaled to match intensity levels and combined. Initial tests of the flatfields did not yield satisfactory results because there were small, but significant, amounts of scattered light on one part of the detector. We corrected for this scattered light using multiple observations of a standard star on a grid of positions over the detector. We then fit a quadratic surface to the difference between the instrumental magnitude of the star at each point on the grid and the average instrumental magnitude measured on the unaffected parts of the detector. The r.m.s. residual in the photometry after correction with the polynomial was 3%; this was only slight larger than the scatter (2.5%) measured from observations of photometric standards (Sec. 2.3), suggesting that the corrected flat fields were good to about 1%. Subsequent tests of the constancy of the sky level on the galaxy frames indicated that the accuracy of the flattening process was significantly better than this (below).

We created average sky frames for each sequence of galaxy observations from the sky exposures which immediately preceded and followed the galaxy frames. These were combined using a median operation to remove stellar images. The appropriate average sky frame was subtracted from each galaxy frame, which effectively removed not only the sky emission but also the dark current and some gross additive features caused by scattered light. The sky-subtracted frames were then divided by the corrected twilight flat fields and multiplied by a bad pixel mask to remove recurring bad pixels from subsequent analysis. To retain the correct count levels for error calculations, a constant equal to the mean of the subtracted sky frame was added back onto each galaxy frame. Note that the mean of the subtracted sky frame is not necessarily identical to the sky value on the galaxy frame because sky levels can fluctuate rapidly in the IR. Determination of a sky value to subtract from the final processed galaxy image is discussed below.

All the frames for an individual galaxy were then aligned to a single reference position using the centroids of 3 to 4 bright stars on the frames. No rotation or difference in scale between the J, H, and K images was evident in a comparison of stellar centroids, so only row and column shifts were required. The alignment was performed using bilinear interpolation with masked bad pixels excluded from the calculation. Tests of the alignment routine using artificial stars showed slight smoothing in the direction of the shift but no significant change in the stellar FWHM. The aligned galaxy frames were additively scaled to match the sky levels, then combined using a weighted average based on the photon statistics and detector read noise. At each pixel position, individual pixel values that were more than 5σ from the mean of all others in the stack were rejected from the calculation.

The final reduction step before photometric calibration was to determine and subtract

an accurate sky value for each galaxy image. None of the galaxies fill the frames and most have only a few bright stars in the field. Thus we could determine the overall sky level by averaging the modal sky values taken in four different boxes on blank regions of the frame. The r.m.s. scatter in the sky levels in different portions of the frame, which is a measure of the accuracy of flat fielding and scattered-light removal, were $\approx 0.2\%$ of the sky level at J and H (corresponding 21.1 and 20.7 mag arcsec^{-2} respectively) and 0.1% at K (corresponding to 19.7 mag arcsec^{-2}).

2.3. Photometric Calibration

All of our calibrated magnitudes and colors are on the CTIO/CIT system. Because nearly all of the faint Elias *et al.* 1982 CTIO/CIT standards were too bright to be observed with OSIRIS, we observed the faint UKIRT standards (Casali & Hawarden 1992. We then converted these onto the CTIO/CIT system using the transformation of Casali & Hawarden (1992). The UKIRT standards do not span a large enough range in color to determine the color term between OSIRIS and the CTIO/CIT system, so we determined a color term from observations of the IR standards of Carter & Meadows (1994) and red stars in the Coalsack obtained on 26 and 28 January 1994 at CTIO with the same telescope and instrumental set-up (Jones *et al.* 1980; Ali 1995).

Holding the color term (derived above) fixed, we obtained zero points, airmass terms, and where appropriate, a UT term for each night of our galaxy observations. Although all nights were photometric, software problems on the first two nights of the run resulted in an inaccurate record of exposure times. Snapshots of galaxies observed on these two nights were taken later in the run and used for calibration. The airmass terms on the remaining five nights did not vary significantly and weather conditions were relatively constant, so we used the same average airmass term on all nights. The transformation equations for each night are of the form:

$$\begin{aligned} K &= k + 0.011(J-K) + c_1 - 0.054X \\ J-K &= 0.952(j-k) + c_2 - 0.017X[+c*UT] \\ H-K &= 0.894(h-k) + c_3 + 0.014X \end{aligned}$$

where capital letters denote magnitudes on the CTIO/CIT system, small letters denote OSIRIS instrumental magnitudes, c_1, c_2, and c_3 are the zero points, and X is the airmass. The zero points remained constant within the errors from night to night, and a UT term was required only on 28 December for the J filter. Figure 1 shows the residuals in K, $J-K$, and $H-K$ vs. color and magnitude for all nights. The r.m.s. residuals in the

transformations are ≤ 0.025 mag, which we take to be the error in our calibration.

We compared photometry in synthetic apertures on our calibrated images to published aperture photometry available in the literature for several galaxies in our sample (Aaronson *et al.* 1982; Devereux 1989; Aaronson *et al.* 1989; Bothun & Gregg, 1990). Table 2 shows the differences in aperture magnitudes in the sense ours *minus* published. Our photometry agrees with the previous values to within a few hundredths of a mag for most of the apertures larger than $10''$. Discrepancies in the large aperture ($\geq 10''$) photometry for NGC 2613 and NGC 3717 are likely due to difficulties in correcting for the presence of bright stars within the aperture. For apertures less that $10''$ in diameter, our photometry is consistently brighter than the aperture values. Photometry in small apertures can be subject to significant seeing and alignment effects; Terndrup *et al.* (1994) also note disagreement between synthetic aperture measurements from arrays and single channel photometry for apertures $\leq 10''$.

2.4. Color Maps and Color Profiles

We computed color maps and profiles in $J-K$, $H-K$, and $J-H$ by aligning the appropriate pairs of images for each galaxy, then computing the colors at each pixel. Examples of the surface brightness and color maps are shown in Figure 2, which displays maps in K and $J-K$ for IC 2531. Figure 3 displays $J-K$ color profiles along the minor axis for each galaxy. We set the minor axis position angle to 90° from the major axis position angle given in the RC3. Colors were measured at one-pixel intervals along a cut through the center of the galaxy, which were measured in the K band to minimize the effects of dust.) Because the galaxy axes were not necessarily aligned with those of the detector, each point along the minor axis was not typically centered on a pixel. The color at each location was therefore taken as the average of surrounding pixels weighted by the distance of each pixel from the non-integer position at which the color is desired. The error bars on the colors represent photon statistics in the images, including the contribution from the night sky, but do not include errors in the photometric calibration which (above) are about 0.025 mag.

The color maps and profiles show red features in areas affected by absorption from dust in the disk, but the bulge colors in regions away from the dust lanes and galaxy nuclei remain relatively constant. The most highly inclined systems in our sample – NGC 1886, IC 2531, and NGC 3390 – have red dust lanes along the major axis, bisecting the bulge. In systems at slightly lower inclinations, such as NGC 1055, NGC 1589, and A0908–08, the red dust lane is displaced from the major axis and one side of the bulge appears to be reddened

by disk dust. Some of the galaxies, for example NGC 3717, have very red nuclei. The blue color near the center of NGC 1964 is due to a foreground star superposed on the galaxy. In general, dust lanes in the edge-on galaxies appear as red peaks in the profiles while systems of lower inclination show asymmetric bulge colors with one side redder than the other.

As a function of inclination, our minor axis color profiles share many of the qualitative characteristics of the $B - I$ profiles presented in Byun *et al.* (1994). Those profiles are calculated from models of radiative transfer in systems consisting of a disk with a dust layer and a dust-free bulge component. We will not attempt to compare these models to our IR data in a quantitative fashion because dust effects can be quite different at optical and infrared wavelengths.

3. Models of Dust Absorption and Scattering

In this section we describe several different models of radiative transfer through dusty media that yield quantitative estimates of reddening and extinction; we compare the predictions of these models to our color profiles in Sec. 4, below. Total extinctions and color excesses are predicted as a function of some measure of total dust quantity, here the total V–band optical depth $\tau_{\rm V}$ through the galaxy. Models of dust distributions can be divided into two types: simple models with analytical representations of radiative transfer and complex ones that require a full numerical solution of the transfer equation. Simple models consider absorption but not scattering and can only be constructed for a few specific dust geometries. The complex models used here, those of WTC92, treat both absorption and scattering for different dust geometries representing various types of galaxies. It is important to note that all of the models discussed here have smooth distributions of dust, whereas observations of the Milky Way and nearby galaxies show irregular and patchy dust features.

3.1. Analytic Models

The simplest and most common representation of dust in galaxies is the plane-parallel foreground screen model, in which an obscuring layer of dust absorbs light from a source behind it. In the absence scattering, the total intensity observed through the dust is given by $I(\lambda) = I_0(\lambda)e^{-\tau_\lambda}$, where $I_0(\lambda)$ is the unattenuated intensity from the source and τ_λ is the

optical depth. The total extinction at any wavelength is then given by

$$\begin{aligned} A_\lambda &\equiv -2.5\log_{10}\frac{I(\lambda)}{I_0(\lambda)}, \\ &= 1.086\tau_\lambda. \end{aligned}$$

Because the wavelength dependence of absorption by dust grains in other galaxies is poorly known (but see Jansen *et al.* 1994), it is common to assume a Galactic reddening law to express optical depth τ as a function of wavelength. Here we adopt the extinction law of Rieke & Lebofsky (1985). Color excesses $E(\lambda_2 - \lambda_1) = A_{\lambda_2} - A_{\lambda_1}$ can then be computed from the adopted reddening law. Figure 4 shows the K–band extinction A_K and the color excesses $E(J-K)$ and $E(H-K)$ as a function of τ_V for the foreground screen model. This predicts a large degree of reddening from low optical depths because all of the light must pass through the dust layer.

Another simple dust model is that of a uniform mixture of dust and stars. Walterbos & Kennicutt (1988) derive:

$$A_\lambda = -2.5\log_{10}\left(\frac{1-e^{-\tau_\lambda}}{e^{-\tau_\lambda}}\right).$$

in the case of a slab with an equal mixture of stars and dust. We plot A_K, $E(J-K)$, and $E(H-K)$ as a function of τ_V for this model in Figure 4, where as above the Galactic extinction law was used to express τ_λ. For the same optical depth, this model produces less reddening than the foreground screen because light from sources near the edge of the mixture escapes with little or no extinction.

3.2. Numerical Models

WTC92 calculate numerical models of radiative transfer in spherically symmetric systems and include the effects of both absorption and scattering. These models are not ideal representations of spiral galaxies because of their spherical shape and smooth dust distributions, but they provide valuable insight into how different assumptions about the distribution of the dust yield different color changes as a function of total optical depth. The fraction of light observed directly and the fraction scattered into the line of sight are tabulated in WTC92 for several wavelengths ranging from the ultraviolet to near-infrared. The extinction at some wavelength λ is given by the relation

$$A(\lambda) = -2.5\log_{10}\left(\frac{I_{direct}}{I_0} + \frac{I_{scatt}}{I_0}\right). \quad (3\text{-}1)$$

We select three of the WTC92 dust geometries for use in our quantitative comparison of model and observed color excesses; these are called the “dusty galaxy,” “starburst galaxy,” and “dusty galactic nucleus” models. The dusty galaxy is a sphere of uniformly mixed stars and dust that differs from the simple uniform mixture model due to the spherical geometry and the inclusion of scattering. Because light is scattered into the line of sight and because sources near the surface suffer little extinction, there is much less reddening at each $\tau_{\rm V}$ than is produced by the simple foreground screen. (Recall that it is the extinction as a function of optical depth which distinguishes the various models.) The starburst galaxy has a centrally concentrated spherical distribution of stars with a uniform sphere of dust embedded in it. Most of the light in this model comes from the central dusty regions, so reddening effects are more pronounced than for the dusty galaxy. The dusty galactic nucleus model contains a sphere of stars surrounded by a spherical shell of dust, with no mixing of dust and light sources in either region. This model differs from the simple foreground screen mainly due to the inclusion of scattering, which compensates for some of the absorption to produce slightly less reddening than the screen model. Extinctions and color excesses are calculated for J, H, and K for these models, and the results are presented as a function of $\tau_{\rm V}$ in Figure 5.

3.3. The Treatment of Scattering

Although scattering is often neglected in favor of retaining simplicity in dust models, it may have considerable effects on the observed extinction characteristics. Scattered light partially compensates for absorption, and reddening effects on colors are less severe because light of shorter (bluer) wavelengths is preferentially scattered into the line of sight. The role of scattering depends strongly on the geometrical distributions of dust and stars as well as the dust grain albedo and angular scattering properties. The models adopted here assume albedos of 0.36, 0.28, and 0.20 for J, H, and K respectively and phase function asymmetry parameters of 0.15, 0.04, and 0.00 in these bands. Figure 6 shows the percentage of observed light that is due to scattering into the line of sight for several of the WTC92 models. Contrary to what may be expected, scattering effects are not largest at the highest optical depths because so much light is absorbed in these cases that there is little left to be scattered (WTC92). This is evident from comparing scattering at $\tau_{\rm V} = 1$ (upper panel) and $\tau_{\rm V} = 5$ (lower panel). We note that scattering is probably not significant for the infrared photometry presented in this paper, since the scattering fraction for $\tau_{\rm V} < 5$ is always less than 10%. However, the effects of scattering will be different at shorter wavelengths as extinction optical depths τ_λ are higher, scattering is less isotropic, and dust grain albedos may be higher (WTC92, but recent models and observations (Witt *et al.* 1994; Kim *et al.*

1994) suggest a K albedo as high as the optical values of 60 to 70% instead of the lower values of 20 to 30% in the standard dust mixture of Draine & Lee (1984)).

Byun *et al.* (1994) find that scattering effects can be ignored for galaxies with inclinations $i > 85°$ because little light is scattered into the plane of the disk. However, even at inclinations as high as 70°, neglect of scattering can contribute to errors of several $\times$ 0.1 mag in the predicted total B band magnitude (Byun *et al.* 1994). On the other hand, Emsellem (1995) finds that scattering effects are necessary to simultaneously explain the B, V, R, and I band attenuation in the dust lane of NGC 4594 ($i = 84°$) and that much more dust is required to explain the observed extinction if scattering is considered than if it is neglected. In general, the above discussion suggests that estimates of the total extinction must be based on models with both absorption and scattering unless it is certain that a particular galaxy has a dust geometry or inclination for which scattering is unimportant.

4. Comparison of Dust Models to the Minor-Axis Colors

4.1. Method of Analysis

We now compare predictions from models of dust extinction to the minor-axis colors of our sample galaxies. For each point along the minor axis which experiences reddening within the galaxy, the intrinsic colors $(J-H)_0$, $(H-K)_0$ would be observed at redder colors; for each dust model the reddened minor-axis colors would be spread out along the path given by $(J-H)_0 + E(J-H)$ and $(H-K)_0 + E(H-K)$ as a function of $\tau_{\rm V}$. In the simple foreground-screen model, $E(J-H) \propto E(H-K)$ and so we have the traditional reddening "vector" in the two-color plot. In other dust geometries or when scattering is included, the ratio $E(J-H)/E(H-K)$ is not constant and the behavior of the two colors with increasing optical depth follows a curved path, which we will term the color "trajectory" of each model. Therefore the distribution of colors along the minor axis in the two-color plane allows us to explore whether any of the simple analytic or numerical models described above are appropriate models of the effects of dust in our sample.

To compare the minor-axis colors to the dust models, we assume that the extinction from the disk is negligible in the outer parts of each bulge (away from the plane of the galaxy). Our assumption is supported by the color profiles in Figure 3, in which the bulge colors are typically constant with minor-axis distance away from the dust lane. We use the color maps and minor-axis color profiles to select a location away from the plane in each galaxy which has constant colors and small errors; the colors at this point are taken to be the intrinsic bulge colors $(J-H)_0$ and $(H-K)_0$. We match each dust model at $\tau_{\rm V} = 0$ to

these colors. In galaxies that are almost edge-on, for example IC 2531 and NGC 3390, the dust lane bisects the bulge along the major axis and bulge colors are equal within the errors on both sides. For these systems we average the outer bulge colors on either side of the dust lane. Galaxies that are not edge-on exhibit more reddening on the side obscured by the dusty disk. In this case, we adopt colors from the outer bulge regions on the unobscured side. Table 3 summarizes the adopted unreddened bulge colors for each galaxy.

The outer-bulge colors in our sample compare favorably to the colors measured for other galaxies. Figure 7 shows the $(J-H)_0$, $(H-K)_0$ values (filled points), along with the nuclear colors (from aperture photometry) for a sample of Sc galaxies (open points) from Frogel (1985). In this figure only, our colors and Frogel's have been corrected for Galactic reddening using the absorption-free polar cap model of Sandage (1973) and the Rieke & Lebofsky (1985) extinction law. That the colors for the two samples are similar suggests that our assumption that the outer bulge colors are relatively unreddened is not too far off. Some of the Sc nuclei are redder at both $J-H$ and $H-K$ than our galaxies, possibly due to dust features contained in the apertures (Frogel 1985).

4.2. Comparison to the Models

Figure 8a–o show $J-H$, $H-K$ diagrams for galaxy colors along the minor axis. The colors are taken from both sides of the galaxy center out to where the intrinsic color was measured. Each plot also shows the color trajectories for the models discussed above. For most galaxies, we assume that $\tau_{\rm V}=0$ corresponds to the intrinsic colors measured in the previous section. Exceptions to this assumption for some individual galaxies are discussed below.

Many galaxies in our sample, particularly the ones of lower inclination, do not have enough reddening to distinguish between different models because all of the models follow the same trajectory at low $\tau_{\rm V}$. Three galaxies – NGC 1325, NGC 2613, and NGC 2713 (Figure 8a–8c) – have no identifiable dust lanes or have dust features located near the edge of the galaxy where the signal-to-noise is too low to determine reliable colors. (For NGC 2613, in which the dust lane is visible at the outer edge of one side of the disk, we locate $\tau_{\rm V}=0$ for the models at the blue edge of the dust feature and consider only the color change across these pixels.) Four other systems – NGC 1515, NGC 1589, NGC 1964, and IC 2469 (Figure 8d–8g) – have dust features that are not red enough to extend into the regime on the color-color plot where different models can be distinguished. As noted earlier, NGC 1964 has a star superposed near the center of the galaxy that has bluer IR colors than the bulge itself. Points bluer than the adopted unreddened color of this galaxy (shown as

asterisks in Figure 8f) are affected by the presence of the star and are ignored in the model comparisons. NGC 1589 has extremely red nuclear $H-K$ colors which are identifiable in the color-color plots as points with low errors (due to the high signal-to-noise in the center) lying far to the red of the model predictions in $H-K$. These points (asterisks in Figure 8e) are ignored in the analysis.

The minor-axis colors of most of the remaining galaxies in our sample – NGC 1886, NGC 1888, ESO 489–29, A0908–08, IC 2531, and NGC 3390 (Figure 8h–8m) – follow the trajectories described by the simple foreground screen and uniform mixture models and the starburst galaxy model of WTC92. The large scatter of points for NGC 1886 also allows for the possibility that the dusty galaxy nucleus model could fit the data, but the trajectory of the data points does not follow the curve of this model. NGC 3717 (Figure 8n), like NGC 1589 above, has extremely red nuclear colors in $H-K$. Neglecting these points (asterisks in Figure 8n), we find that the reddening on the red side of the bulge (open points in Figure 8n) is also described by the foreground screen, uniform mixture, and starburst galaxy models. We have located the $\tau_{\rm V}=0$ point for the models at the bluest color of the red (obscured) side of the NGC 3717 bulge because the colors on the red side follow a reddening trajectory while those on the blue side (solid points in Figure 8n) are relatively constant.

The JHK colors of NGC 1055 are quite different on the obscured and unobscured sides of the bulge. Here we select two locations for $\tau_{\rm V}=0$ of the models, one for each side. Clearly the bluest color of the red (obscured) side is not actually free of reddening, but this is not important because we are interested in the change in color across the dust feature. The curved trajectory of colors on the blue side of NGC 1055 (open circles in Figure 8o) resembles the behavior of the dusty galactic nucleus model at high $\tau_{\rm V}$, where it strongly deviates from the other models by curving in the opposite direction. As described in Sec. 3, the dusty galactic nucleus model is basically a foreground screen with the inclusion of scattering. It is possible that in this case, we are observing disk stars through a dust lane at an angle at which scattering effects are important. The outer-bulge colors we measured may not be completely free of reddening even for the blue side of the bulge; this would explain why the model diverges from the simple foreground screen at high $\tau_{\rm V}$ while our data diverge at what we have called $\tau_{\rm V}=0$. The colors on the red side of NGC 1055 (solid circles in Figure 8o) do not appear to follow any of the model trajectories.

Dust geometries with a significant fraction of light sources located near the edges of the system never produce enough reddening to explain the extremely red dust lane colors observed in the most highly inclined galaxies in our sample. Because the bulk of the IR light seen in a highly inclined disk galaxy is located behind the dusty disk in the bulge, it is reasonable that models with unobscured light sources do not match the observations

as well as screen-type models. This is particularly apparent in the dusty galaxy model of WTC92: the colors level off at some optical depth and there is little or no more reddening with increasing τ_{V}. The starburst galaxy model of WTC92 and the simple uniform model also show this saturation effect, but it occurs at redder colors than in the case of the dusty galaxy so these two models can still describe many of the observed dust lane colors.

For two cases of models with analogous dust distributions, we find that the simple models with no scattering provide a better description of the color trajectory than the numerical models that include scattering. The simple uniform model appears to be a much better fit to the observations than the analogous dusty galaxy model of WTC92, which has a trajectory that curves sharply blueward in $J-H$ at high τ_{V}. Likewise, the simple foreground screen model lies along the observed color trajectories while the analogous dusty galactic nucleus model of WTC92 has a color trajectory that curves away from the observations and the other models considered here. These results are not surprising: scattering is not expected to be important in the IR for the highly inclined galaxies in our sample because most of the light is from red bulge stars located behind the "screen" of the dusty disk and thus little is scattered towards the observer. However, we note that the mixture of dust and light sources that would be seen in a face-on system or in an edge-on galaxy at blue wavelengths (where the young stars in the spiral arms are visible) would produce more scattering and would also require a different model geometry.

4.3. Dust Optical Depth in Highly Inclined Galaxies

We now measure maximum color excesses in galaxy dust lanes to estimate the range of total V band optical depth predicted by various dust models. The sample is limited to those galaxies with clearly defined dust lanes and JHK colors that follow the model reddening trajectories from the intrinsic colors out to the reddest values. Columns 3–5 of Table 4 give the maximum $E(J-K)$, $E(H-K)$ and $E(J-H)$ measured along the minor axis. Corresponding V band optical depths at each color for each appropriate dust model are given in Columns 6–8 of Table 4. (For NGC 1589, we ignore the extremely red nuclear points discussed above and use the reddest point in the dust lane to calculate color excesses.) The values of τ_{V} predicted from the three different colors of a single galaxy are similar, as is expected if the model adequately describes the observed colors. We take an average of these three values as the estimated τ_{V} for the galaxy and present this and the corresponding K band extinction $\mathrm{A_K}$ for each case in columns 9–10 of Table 4.

It is clear from Table 4 that the total optical depth in dust needed to produce the observed reddening is highly sensitive to geometry (the models all have the same dust

properties, and thus differ primarily in geometry). The simple foreground screen model provides a *lower* limit on the optical depth; other geometries require more dust to produce the same reddening because sources near the edge of the system do not interact with much dust and/or scattering partially compensates for absorption. For the highly inclined galaxies in Table 4, the predicted $\tau_{\rm V}$ from the screen model ranges from 1.6 to 2.7, while corresponding $\tau_{\rm V}$ from the uniform mixture and starburst galaxy models are much higher: 3.7 to 7.5. For two of the edge-on galaxies, NGC 1886 and IC 2531, only the screen model produces enough reddening and the predicted values of $\tau_{\rm V}$ are ≈ 4.5. The colors of NGC 3390 can be represented by either the screen or uniform mixture models: the screen model predicts $\tau_{\rm V} \approx 4.5$ and the uniform mixture yields $\tau_{\rm V} \approx 15$. All of these values imply that the dusty regions of highly inclined galaxies are optically thick at visible wavelengths, but whether or not they would be optically thin at face-on inclinations depends on which model is used to predict $\tau_{\rm V}$ and the assumed ratio of dust scale height to disk scale length.

Figure 9 shows the maximum measured dust lane color excess as a function of distance from the galaxy center along the *major* axis. These values are determined from color profiles of cuts parallel to the minor axis: $E(J-K)_{\rm max}$ is measured for each profile just as it was for the minor axis above. Because the signal-to-noise ratio is usually too low to measure an intrinsic color for cuts parallel to the minor axis, the intrinsic bulge colors derived in Sec. 4.1 are used. (Although many of these cuts pass primarily through the disk rather than the bulge, we note that our color maps show similar $J-K$ for bulge and disk. Terndrup *et al.* (1994) also find bulges and disks to have similar $J-K$ colors.) The three edge-on galaxies of Table 4 show a strong peak in central reddening; this could be due to a concentration of dust at the galaxy center and/or an extremely red nuclear stellar population. In regions away from these three galaxies' centers and in the other three galaxies shown in Figure 9, the maximum dust lane reddening remains relatively constant. In some cases there appears to be a slight tendency for $E(J-K)_{\rm max}$ to diminish with increasing galactocentric distance, which could be due to the fall-off of an exponential disk of dust. Using $A_{\rm V,max}$ instead of $E(J-K)_{max}$, Jansen *et al.* (1994) find a rapid drop in the maximum dust lane extinction at increasing distance from the center for several highly inclined galaxies. If such a decrease in optical depth does occur in our galaxy sample, it may be noticeable at greater distances from the center or in the more dust-sensitive optical colors.

5. Dust and Stellar Population Studies

Figure 10 shows the changes in JHK colors produced by age and metallicity, from the models of Worthey (1992), along with the reddening trajectories of the three models

that best describe galaxy dust lane colors. It is clear that for these colors, the reddening produced by the dust models lies parallel to the color changes that would result from gradients in metallicity and age. Because the quantity of dust is not well constrained, it is impossible to determine how much of a color change along the observed trajectory is due to dust and how much is due to a change in the stellar population. This unfortunate situation greatly limits the use of broad-band photometry for stellar population studies.

Once a dust model is selected to describe reddening within a galaxy, it may be possible to find specific color-color diagrams in which the effects of extinction can be distinguished from changes in stellar population (e.g. Witt 1995). However, the difficulty of using colors as population indicators is also exacerbated by degeneracies in the changes produced by metallicity and by age. Spectral line studies, rather than colors, appear to be a more effective tool to disentangle the effects of dust, metallicity, and age and to study population gradients in spiral bulges.

6. Summary and Discussion

We compare JHK colors across the dust lanes of highly inclined late type spirals to predictions from several different dust models. All of the representations available for quantitative comparisons have smooth dust distributions (no patchy features) and none has precisely the geometry of spiral galaxies. Two common analytical models, the foreground screen and the uniform mixture, provide good descriptions of the observed reddening. The starburst galaxy model of WTC92 also adequately describes the observed color profiles. Dust geometries with a significant fraction of unobscured light sources such as the WTC92 dusty galaxy model never produce enough reddening to match the observed colors in the reddest disk absorption features seen in our galaxy sample. Although the dusty galactic nucleus and dusty galaxy models of WTC92 differ from the simple analytical screen and uniform models only in the inclusion of scattering and the spherical (rather than plane parallel) geometry, they predict very different JHK colors as $\tau_{\rm V}$ increases. The lack of agreement between the models with scattering and the IR dust lane colors of highly inclined galaxies suggests that in the IR, scattering effects are not significant for the objects that make up our sample. However, as noted in Sec. 4.2, both scattering and models that include some unobscured sources may be required to describe face-on systems at any wavelength or galaxies of any inclination at blue wavelengths where young disk stars are visible. Such models would be particularly important for very late type spirals in which a small bulge may no longer be the dominant light source.

Because three different dust models each provide a satisfactory description of the

galaxy colors, we cannot derive a single value for the total optical depth of dust. Instead, we use the three results to place limits on this quantity. In all cases, the simple foreground screen model that is traditionally used to discuss dust extinction provides the lower limit on optical depth τ_V because the light sources interact with all of the dust and there is no scattering to compensate for absorption. Our predicted τ_V for edge-on galaxies ranges from ≈ 4.5 for the screen model up to 15 for the uniform mixture. Values for dust lane optical depth in galaxies that are not exactly edge-on range from near 2 for the screen model to 4 to 7.5 for the uniform mixture and starburst galaxy models. These limits provide guidelines for understanding galaxy optical depths, but they can be narrowed to more precise values only with a better understanding of the geometry and scattering properties of the dust. That models with quite different τ_V give the same reddening leads us to conclude that an estimate of the absorption-free light distribution in *any* edge-on galaxy *requires a proper treatment of radiative transfer.* In our future papers, we will analyze our optical data for these galaxies using the procedures developed in this paper. This will help determine which dust models can describe the observed colors over a long spectral baseline, including the more dust-sensitive blue wavelengths.

There are inherent difficulties in our method of selecting intrinsic bulge colors that should not be overlooked, but these have little impact on our qualitative conclusions about dust models. By assuming that the outer bulge colors are not reddened, we imply that there is little or no dust mixed in with the bulge component. The constant outer bulge colors evident in our data and the similarity between our intrinsic colors and the colors of lower inclination Sc galaxies from Frogel 1985 suggest that there is indeed little or no reddening in the outer bulge. We have also assumed that the intrinsic colors of the inner and outer bulge are the same in order to measure a color excess in the dust lane. This neglects any change in color due to a stellar population gradient. If we assume a metallicity change of ≈ 0.4 dex, consistent with that measured for the Milky Way bulge (e.g., Terndrup 1988; Frogel *et al.* 1990; Terndrup *et al.* 1990; Tiede *et al.* 1995), the corresponding color change would be ≈ 0.15 in $J-K$ based on the stellar population models of Worthey (1992). This is much smaller than the total color change across the dust lanes (see Table 4), suggesting that the observed $J-H$ and $H-K$ color changes are for the most part due to dust extinction. Finally, it is possible that blue light scattered from the side of the disk located behind the bulge may contribute to a slight bluing of the unobscured side. Although all of the factors mentioned here may contribute to errors in the total τ_V values we measure, they do not affect the basic trajectories in the color-color diagrams and thus will not change our conclusions about which models best describe the observations.

Our study of dust extinction in late-type spirals can help pinpoint where mass models based on the light distribution are likely to be inaccurate, an important step in

understanding dynamical influences on the bulge and inner disk. We predict values of $A_K \approx 0.5 - 0.6$ at the centers of edge-on galaxies and $0.2 - 0.3$ in the dust lanes of highly inclined galaxies that are not exactly edge-on (Table 4). In fact, once a plausible dust model is specified, the extinction A_λ at any wavelength can be determined for any location based on the reddening at that point. These extinction values can be used to understand how the mass to light ratio (M/L) changes over galaxy dust features or even to crudely correct the light distribution so that a constant M/L can be invoked. Combined with kinematical data, an improved picture of the stellar light distribution in the inner regions of spirals will shed light on the interaction between disks and bulges. It will then be possible to address questions about the history of the bulge and disk components, the relation between bars and bulges, and why some galaxies have boxy or peanut-shaped bulges.

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Fig. 1.— Magnitude and color residuals for the photometric calibrations, in the sense published values for the standard stars *minus* our values. Photometry is on the CTIO/CIT system. Data are shown for all 5 nights on which calibrations were carried out.

Fig. 2.— Contour plots of the K-band surface photometry and $J-K$ color map for IC 2531, an example of an edge-on galaxy in our sample. North is on the bottom and East is to the left.

Fig. 3.— Color profiles along the minor axis of each galaxy. The errorbars represent uncertainties due to photon statistics and sky noise in the J, H, and K images; they do not include calibration errors. Galaxy inclination angles estimated from Bottinelli *et al.* (1983) are given in the upper right of each panel.

Fig. 4.— K band extinction $\mathrm{A_K}$ and color excesses $E(J-K)$ and $E(H-K)$ as a function of τ_V for the simple foreground screen and uniform mixture models. The Galactic reddening law of Rieke & Lebofsky (1985) has been used to express $\tau(\lambda)$ as a function of τ_V for the model calculations.

Fig. 5.— K band extinction $\mathrm{A_K}$ and color excesses $E(J-K)$ and $E(H-K)$ as a function of τ_V for the radiative transfer models of WTC92. The scale identical to that of Fig. 4 to facilitate comparison.

Fig. 6.— Fraction of observed light that has been scattered into the line of sight as a function of wavelength for WTC92 dust models with $\tau_\mathrm{V} = 1$ (upper panel) and $\tau_\mathrm{V} = 5$ (lower panel).

Fig. 7.— Adopted outer-bulge $J-H$ and $H-K$ colors of galaxies in our sample (filled squares) and nuclear colors of Sc galaxies from Frogel (1985) (open circles). The locations of dwarf stars and giants in globular clusters, the local field, and Baade's Window are shown for comparison.

Fig. 8.— $J-H$, $H-K$ diagrams for galaxy minor axis colors. Errors in the colors are calculated from photon statistics and sky noise on the J H, and K images. Typical calibration errors are shown in the lower right corner of each plot. The reddening trajectories predicted by different dust models are shown as lines originating at the $\tau_{\rm V}=0$ locations discussed in Sec. 4.2. For NGC 1055 and NGC 3717, which have different color trajectories on the obscured and unobscured sides of the bulge, the colors on one side are denoted by open points and those on the other side are denoted by closed points. Central points of NGC 1589, NGC 1964, and NGC 3717 are ignored as described in the text; these are denoted with starred points on the plots.

Fig. 9.— Maximum $J-K$ color excess in cuts across the dust lane as a function of distance of that cut from the galaxy center (along the major axis). Errorbars are calculated from the errors in the intrinsic and reddest colors, which reflect photon statistics and sky noise on the J and K images.

Fig. 10.— Changes in IR colors produced by age (left panel) and metallicity (right panel) from the stellar population models of Worthey (1992). Ages range from 8 to 17 Gyr for [Fe/H] = 0.0, metallicity is from [Fe/H] = -1.0 to $+0.25$ for an age of 12 Gyr. Reddening trajectories predicted by the dust models that describe highly inclined spirals are shown on both plots, with $\tau_{\rm V}=0$ located at the bluest (youngest or most metal poor) stellar population colors.

Table 1. Basic Galaxy Data and Log of Observations

Galaxy	Type[a]	B/P[b]	B_T[a]	incl.[c]	log D_{25}[a,d]	J[e]	H[e]	K[e]
NGC 1055	SBb	yes	11.40	72	1.88	585	585	700
NGC 1325	Sbc	no	12.22	73	1.67	585	585	700
NGC 1515	Sbc	no	12.05	82	1.72	585	585	700
NGC 1589	Sab	yes	12.80	75	1.50	585	585	700
NGC 1886	Sbc	yes	13.60	90	1.49	390	390	700
NGC 1888	SBc	yes	12.83	77	1.48	585	585	700
NGC 1964	Sb	no	11.58	70	1.75	585	565	700
ESO 489−29	Sbc	yes	13.33	90	1.47	585	585	820
NGC 2613	Sb	no	11.16	80	1.86	315	315	700
NGC 2713	SBab	no	12.72	68	1.56	585	585	700
A0908−08	Sb	no	11.91	81	1.63	585	585	700
IC 2469	SBab	yes	···	85	1.67	390	315	700
IC 2531	Sc	yes	12.90	90	1.84	585	585	700
NGC 3390[f]	Sb	yes	12.85	90	1.55	700	700	1050
NGC 3717	Sb	no	12.24	88	1.78	585	585	820

[a]Data from the RC3.

[b]B/P = boxy or peanut-shaped bulge identified in Jarvis (1986), de Souza & dos Anjos (1987), or Shaw *et al.* (1990).

[c]Inclinations estimated from Equations 1 and 2 in Bottinelli *et al.* (1983).

[d]log D_{25} in units of 0.1 arcmin.

[e]J, H, and K exposure times in seconds.

[f]NGC 3390 is classified as either $S0_3$ (S0 with dust lane) or Sb in Sandage & Bedke (1994).

Table 2. Comparison to Published Aperture Photometry

Galaxy	Aperture	ΔJ[a]	ΔH[a]	ΔK[a]
NGC 1055[b]	81.2	···	−0.05	···
	110.6	···	−0.01	···
NGC 1325[b]	55.8	···	−0.02	···
	70.1	···	−0.01	···
NGC 1964[b,c]	3.6	···	−0.05	−0.14
	5.3	···	···	−0.18
	7.2	···	···	−0.25
	9.3	···	−0.22	−0.29
	53.4	···	−0.03	···
	81.2	···	−0.10	···
	105.0	···	−0.05	···
	110.6	···	−0.10	···
NGC 2613[b]	83.6	···	−0.17	···
	110.0	···	−0.19	···
IC 2531[d]	59.2	···	−0.07	···
	69.5	···	−0.09	···
NGC 3390[e]	10.0	−0.18	−0.19	−0.20
NGC 3717[b]	50.4	···	−0.15	···
	81.2	···	−0.15	···

[a]Δmag in the sense (ours–published).

[b]Aaronson *et al.* 1982.

[c]Devereux 1989.

[d]Aaronson *et al.* 1989.

[e]Bothun & Gregg 1990.

Table 3. Adopted Intrinsic Bulge Colors

Galaxy	$r(i)$[a]	$J-K$	error	$H-K$	error	$J-H$	error
NGC 1055	−6.6	0.91	0.04	0.30	0.04	0.61	0.03
NGC 1325	+8.8	0.81	0.17	0.16	0.15	0.66	0.12
NGC 1515	+5.5	0.97	0.04	0.27	0.03	0.71	0.03
NGC 1589	+8.8	0.92	0.08	0.22	0.06	0.70	0.06
NGC 1886	−4.4	0.82	0.11	0.21	0.07	0.61	0.10
NGC 1888	+5.5	0.98	0.05	0.27	0.04	0.71	0.04
NGC 1964	−6.6	0.98	0.03	0.28	0.02	0.70	0.02
ESO 489−29	−5.5	0.89	0.07	0.24	0.06	0.65	0.06
NGC 2613	+7.7	0.92	0.11	0.21	0.05	0.71	0.12
NGC 2713	−7.7	1.00	0.05	0.26	0.04	0.74	0.04
A0908−08	+8.8	0.88	0.06	0.23	0.05	0.66	0.04
IC 2469	−4.4	0.95	0.05	0.27	0.02	0.68	0.05
IC 2531	±6.6[b]	0.96	0.10	0.27	0.09	0.70	0.08
NGC 3390	±6.6[b]	0.92	0.06	0.25	0.05	0.67	0.05
NGC 3717	−8.8	0.85	0.04	0.20	0.03	0.65	0.03

[a] $r(i)$ = distance in arcsec from center (along minor axis) at which intrinsic colors are measured.

[b] For edge-on galaxies, colors on both sides of the bulge are averaged.

Table 4. Total Optical Depth in Galaxy Dust Lanes

Galaxy	Model	$E_{\rm JK}$[a]	$E_{\rm HK}$[a]	$E_{\rm JH}$[a]	$\tau_{\rm V,JK}$[b]	$\tau_{\rm V,HK}$[b]	$\tau_{\rm V,JH}$[b]	$\langle\tau_{\rm V}\rangle$[c]	$\langle A_{\rm K}\rangle$[c]
Edge-On Galaxies									
NGC 1886	screen	0.80	0.31	0.50	4.36	4.49	4.29	4.38	0.53
IC 2531	screen	0.81	0.30	0.52	4.40	4.33	4.44	4.39	0.53
NGC 3390	screen	0.79	0.35	0.44	4.29	5.07	3.82	4.39	0.54
NGC 3390	uniform	0.79	0.35	0.44	14.89	15.37	14.24	14.84	0.78
Highly Inclined Galaxies									
NGC 1589	screen	0.31	0.11	0.20	1.65	1.55	1.71	1.64	0.20
NGC 1589	uniform	0.31	0.11	0.20	3.77	3.37	4.04	3.73	0.22
NGC 1589	starburst	0.31	0.11	0.20	3.98	3.57	4.20	3.92	0.24
ESO 489-29	screen	0.43	0.15	0.28	2.31	2.18	2.38	2.29	0.28
ESO 489-29	uniform	0.43	0.15	0.28	5.63	4.94	6.17	5.58	0.32
ESO 489-29	starburst	0.43	0.15	0.28	6.02	4.97	6.91	5.97	0.36
A 0908-08	screen	0.49	0.18	0.31	2.66	2.66	2.66	2.66	0.32
A 0908-08	uniform	0.49	0.18	0.31	6.78	6.24	7.21	6.75	0.38
A 0908-08	starburst	0.49	0.18	0.31	7.33	6.41	8.18	7.31	0.43

[a]$E_{\rm JK} = E(J-K)$, $E_{\rm HK} = E(H-K)$, $E_{\rm JH} = E(J-H)$.

[b]$\tau_{\rm V,JK} = \tau_{\rm V}$ determined from $E(J-K)$, likewise for other colors.

[c]Values for $\langle\tau_{\rm V}\rangle$ and $\langle A_{\rm K}\rangle$ are averages of the values determined for each of the 3 colors.